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Power Control for Wind Turbines in Weak Grids: Donegal Case

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March 1999

Abstract The current report is a summary of the results of the case study done at Donegal in the context of the EU supported project 'Power Control for Wind Turbines in Weak Grids', contract no JOR3-CT95-0067. In this project various combinations of wind power, storage and control are studied in order to increase the amount of wind energy that can be absorbed economically at a given point in a weak grid.

The project consists of four main parts. The first part is concerned with the development of such systems. Mainly battery and pumped storage are considered as storage and different control strategies are studied. The second part is the development and test of a power control system using batteries. The third and fourth parts are two case studies in Madeira, Portugal and County Donegal, Ireland.

The scope of the analysis is to investigate if the amount of wind energy that can be utilised in Donegal can be economically increased especially seen from a power control point of view. The power system of Donegal is weak. This limits the both the amount of wind energy that can be installed and the consumer load, which limits the development of the region.

The main result is that with the current fuel prices the generation cost of energy using gas turbines is the least cost option. However, it is very important that future development in the fuel cost is taken into consideration before decisions on which option to chose.

An optimised design for a pumped storage plant could reduce the investment cost considerably and increases in the fuel cost is also likely to happen. The generation cost from wind energy in County Donegal is quite low due to the very good wind resource in the region. This combined with the increased certainty of the production cost during the life time of the installation make it worth while to consider installation of additional wind power in combination with a pumped storage plant.

One additional factor that has to be taken into consideration is the general development of the region. In this development an improved power supply can play a crucial role.

It is recommended that further investigations especially including local and utility planners in order to have a more complete picture of the development of the region and the possibilities and requirements for that development.

Information Service Department, Risø, 1999

Contents

1 Introduction

The current report is a summary of the results of the case study done at Donegal in the context of the EU supported project 'Power Control for Wind Turbines in Weak Grids', contract no JOR3-CT95-0067. In this project various combinations of wind power, storage and control are studied in order to increase the amount of wind energy that can be absorbed economically at a given point in a weak grid.

The project consists of four main parts. The first part is concerned with the development of such systems. Mainly battery and pumped storage are considered as storage and different control strategies are studied. The second part is the development and test of a power control system using batteries. The third and fourth parts are two case studies in Madeira, Portugal and County Donegal, Ireland.

2 Background

In many parts of the world and certainly in Europe large areas exist where the wind resources are good or very good and the grid is relatively weak due to a small population. In these areas the capacity of the grid can very often be a limiting factor for the exploitation of the wind resource.

There are two main problems concerned with wind power and weak grids. The first is the steady state voltage level. When the power consumption is low e.g. during the night the voltage of the grid can increase to levels above the limits if the wind power input is high. The other main problem is voltage fluctuations. Because the wind is fluctuating the output from the wind turbines is also fluctuation. This together with wind turbine cut-ins can result in voltage fluctuations that are above the flicker limit. Some or all the these problems can be avoided if a so-called power control concept is applied together with the wind farm.

The idea behind the power control concept is eliminate the violations of the steady state voltage level by buffering the power from the wind turbines in periods where the voltage limits might be violated and then release it when the voltage level is lower and combine this ability with smoothing of the power output in order to remove power fluctuations that otherwise would create voltage fluctuation above the flicker limit.

The development of such a power control concept has been the objective of an EU-project, 'Power Control for Wind Turbines in Weak Grids', JOR3-CT95-0067.

3 Scope of the Analyses

The scope of the analysis is to investigate if the amount of wind energy that can be utilised in Donegal can be economically increased especially seen from a power control point of view. The power system of Donegal is weak. This limits the both the amount of wind energy that can be installed and the consumer load, which in turn limits the development of the region.

The steps in the analysis are therefore:

- Can more wind energy be absorbed in the power system and a which cost.
- Can more wind turbines be connected to the grid at the most favourable site without violating voltage level limits.
- Can the application of power control concepts increase this amount economically.

The point of view of the analysis is that of the society/system.

4 Summary of the Analysis and Assessments

The wind resources in County Donegal are very good with average wind speeds of more than 9m/s at 30m agl. There is therefore a large potential for wind power in the region.

The analysis has shown that the grid can only absorb a limited amount of wind power and that a very substantial amount of that is already installed. The wind farm at Cronalaght is equipped with a Voltage Control Unit in order to limit the power output from the wind farm in order to avoid over-voltage situations.

There are several sites which are favourable for installation of pumped storage plant of the relevant size. The costs associated with installation of such plants make it reasonable to consider the combination of pumped storage and wind power.

To main scenarios have been studied. The first scenario includes an increase of the existing wind farm with an additional 6*600kW wind turbines. The different alternatives are then dumping all wind energy necessary for keeping voltage below the upper voltage limit, installation of a suitable pumped storage plant and reinforce the grid. The pumped storage is assumed to be installed very close to the wind farm. The second main scenario includes an additional wind farm of 3*600kW with the same alternatives but the pumped storage plant is installed at another site some distance from the wind farm.

The analysis has showed that for the first scenario is the cost of the combined wind farm/pumped storage plant and the grid reinforcement approximately the same so only a more detailed study will be able to find the least cost option. Also other considerations may have to be included in the analysis like possibilities to increase the industrial development etc.

The least cost option for the second scenario is the grid reinforcement. This option is far cheaper than the alternatives.

Both the combination of wind farm and pumped storage from the first scenario and the grid reinforcement in the second scenario have been compared with conventional generation. Gas turbine generation has been chosen since this most likely will be the type of generation that is displaced. This comparison indicated that with the current fuel prices the least cost option is generation using gas turbines. However, it has to be taking into account that the current fuel prices are very low.

5 Conclusions and Recommendations

The main result is that with the current fuel prices the generation cost of energy using gas turbines is the least cost option. However, it is very important that future development in the fuel cost is taken into consideration before decisions on which option to choose.

An optimised design for a pumped storage plant could reduce the investment cost considerably and increases in the fuel costs are also likely to happen. The generation cost from wind energy in County Donegal is quite low due to the very good wind resource in the region. This combined with the increased certainty of the production cost during the life time of the installation make it worth while to consider installation of additional wind power in combination with a pumped storage plant.

One additional factor that has to be taken into consideration is the general development of the region. In this development an improved power supply can play a crucial role.

It is recommended that further investigations especially including local and utility planners in order to have a more complete picture of the development of the region and the possibilities and requirements for that development.

6 Power Control Analysis Framework

The basis of the analysis is a framework that contains all the necessary elements of the technical and the economic analyses. The first element is the data collection in which the necessary data are collected. It is then followed by an scenario definition. In this part the different scenarios that will be investigated are defined. The actual technical analysis is parted in three: power system operation, voltage level and voltage fluctuations. The final part is the economic analysis. The process is iterative since solutions will appear as a result of the analyses.

The framework is considering only the technical and economic performance of wind farms with power control equipment.

6.1 Data Collection

The purpose of the data collection is to establish the foundation of the analyses. The main task is collect the necessary data but it is also important to establish contact with the local authorities.

The main categories of data are

- wind data
- power generation data
- power transmission data
- load data
- forecasts of above
- wind turbine data

6.2 Scenario Definition

The scenarios define the different options that are to be compared. In the current context it will mainly be size of wind farm, type of storage, control strategy and alternatives like grid reinforcement and wind turbine shut down.

On each of these scenarios are technical and economic analyses performed in such a way that the results can be compared.

6.3 Power System Operation

WINSYS, [1], is a power system performance model developed by Risø especially useful for investigating the feasibility of wind energy in isolated power systems. The model is operated inside a spread-sheet environment, making the model user-friendly and flexible.

Model inputs are:

- hour by hour load pattern for week- and weekend-days for winter, spring, summer and autumn,
- hour by hour wind speed distribution for each of the four seasons,
- year by year load forecast,
- specification of existing and planned fossil fuel based power supply system in terms of installed capacity, technical minimum load, fuel type and fuel consumption as a function of the load,
- year by year fuel costs forecast,
- specification of existing wind power installations,
- specification of investigated wind power installation,
- wind power investment cost, operation and maintenance costs, life time and discount rate.

Model outputs are:

- wind energy potential, E_{pot} (MWh/year) and utilised production, AUE (MWh/year),
- dissipated wind energy in case the load is too small to absorb the full wind energy production,
- fuel consumption with and without the assessed wind power installation,
- levelised production cost, LPC (DKK/kWh) of wind energy,

- power supply system short run marginal cost, SRMC (DKK/kWh) with and without the assessed wind power installation.

Optionally, WINSYS can do optimisation and sensitivity analysis on the investigated wind power installation. Figure 1 gives a graphical illustration of WINSYS.

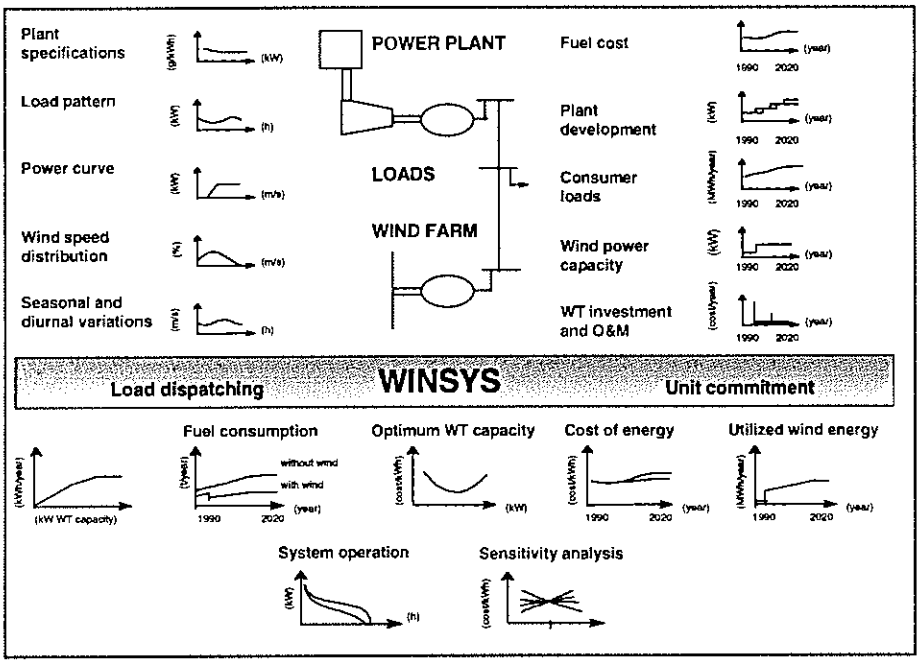

Figure 1 Graphical illustration of WINSYS input and output.

Because the very low penetration level in general in Ireland the operation of the power system is not influenced by the presence of the wind farms studied in this projects context. A WINSYS calculation is not performed in the present case study.

6.4 Steady State Voltage Analysis

The steady state voltage analysis is performed using load flow software. The grid is described in the neighbourhood of the point of the common connection, this can e.g. be the feeder to which the wind farm is connected to the nearest transformer to the next higher voltage level. This then combined with the load description and the wind power production in order to calculate worst, best and most likely cases of the grid voltage along the feeder. Often the criteria is taken as no over-voltages are allowed even in the worst case situation. More elaborate criteria like statistical measures can be applied if a less conservative perspective is used.

In order to calculate the performance of a system that includes wind power and a storage system a model, StorSim, has been developed and implemented.

StorSim includes models of wind turbines, storage system (battery and pumped storage), grid and the control system. Based on generated load and wind speed time series the operation of the system is simulated. The output of the model include steady state voltage, power flow in and out of the storage and state of charge of the storage.

The model also calculate the amount of wind energy that has to be dumped if the voltage limits are not to be violated if the storage system cannot absorb the energy due to limitations in power or storage capacity.

6.5 Dynamic Voltage Behaviour

The determination of the dynamic voltage behaviour is a rather complex matter. It requires dynamics models of the wind turbines as well as of the wind that each wind turbine experiences in order to be able to predict dynamic output from a wind farm.

An assessment of the dynamic behaviour could be relevant for the case in Co. Donegal. The project does not include such an assessment.

7 Wind Energy in County Donegal

Under the AER1 6 projects were located in Co. Donegal representing a total installed capacity of 47.5MW. The present stage (March 1998) of the AER1 and Thermie funded projects in County Donegal is shown in Table 3. Two of the AER1 wind projects in Donegal failed to get planning permission namely Binbane 7.5MW and Tullytressna also 7.5MW. Tullytressna relocated slightly and combined with the Cark 7.5 MW project to make up one windfarm of 15MW. In addition two Thermie funded windprojects, Cronalaght Windfarm and Anagret Upper 1.8MW were located in County Donegal.

Under the AER3 competition only two windprojects out of a total of 17 projects were awarded PPA contracts in Co. Donegal. Information about potential bidders and sites are confidential, it is generally believed there were only one other large project in County Donegal going through to the final assessment. One of the reasons so few projects and particularly large projects were located in County Donegal is in general attributed to the weak ESB network in County Donegal. Out of the total load of approx. 80MW in County Donegal (source Alterner study) almost 45MW will be met by wind by the time the projects under construction are completed. If these projects received planning permission and go ahead wind energy penetration in County Donegal will exceed 75% of total. Potential developers are aware of this and would tend to look elsewhere.

Planning permission has also been obtained for a single turbine (660kW) on the Westcoast of Donegal to self supply a fish processing factory with a very high 24 hour electricity load.

Table 1 Summary Installed Wind energy in Co. Donegal.

Name of Project	Size	Turbines	Commissioning date	Owner/Developer	PPA Contract
Cronalaght	3MW	5xVestas V39-600	May 97	Gineadoiri Gaoithe Teo	Thermie
Barnesmore	15MW	25 x Vestas V42-600	June 97	Scottish Power	AER1
Cark	15MW	25 x Micon 600	Oct. 97	RES/B9	AER1
Drumlough Hill1	5MW	Windmaster	Spring 98	Windmaster/ Treasury	AER1
Crockahenny 2	5MW	Enercon	Spring 98	Enercon/ESC	AER1
Anagret Upper3	1.8MW	3 x Vestas 42-600	Autumn 98	Saporite Ltd	Thermie
Meenadreen	13 MW			Conor Ronan	AER3
Meenadreen	4.8MW			Whaplode Ltd	AER3

8 Wind Energy Assessment

Wind data from the site of one of the Thermie funded wind projects: Cronalaght Windfarm was supplied by ScanEES Ltd. to Risø.

The site at Cronalaght was first identified in the Hurley Staudt Report: *"Identification of Wind Energy-rich sites best suited for WindEnergy Development"*. Department of Transport, Energy & Communication, Dublin 1989. Wind monitoring started in January 1994 and continued until April 1996 at 30m height. The location of the site is shown on Appendix 3. Analysis of the wind data shows an annual mean wind speed of 9,8m/sec at 30m height. Long term correlation of the wind data, carried out by an English independent wind consultant company; Borderwind, shows a reduction of 0.4m/sec in long term wind data. Risø has carried out further analysis of the wind data.
Measured wind speed data from the met. mast at Cronalaght wind farm site is analysed. The data are from January 1994 to July 1995. The met. mast was located in an open area with peat-land, map reference 184200/423920. The measurement height was 30 m above ground level (agl). The wind climatological fingerprint for the measured data is enclosed as Appendix 2.

1 Under Construction

2 Under Construction

3 Construction expected to start summer

Figure 2 shows the average daily variations in wind speed for the four quarters of the year based on data from 1994 and 1995.

Figure 3 shows the wind speed distribution for 1994 with an annual average wind speed of 9.67 m/s and the Weibull fit with A = 10.9 m/s and k = 2.2.

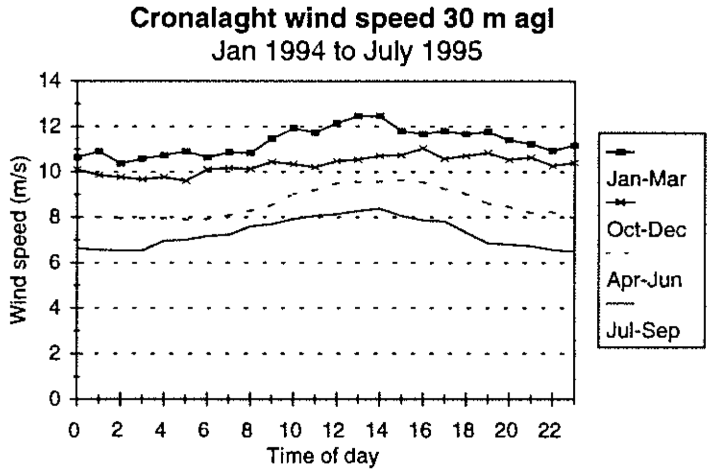

Figure 2 Measured wind speed at Cronalaght wind farm site in 30 m agl. Data from January 94 to July 95.

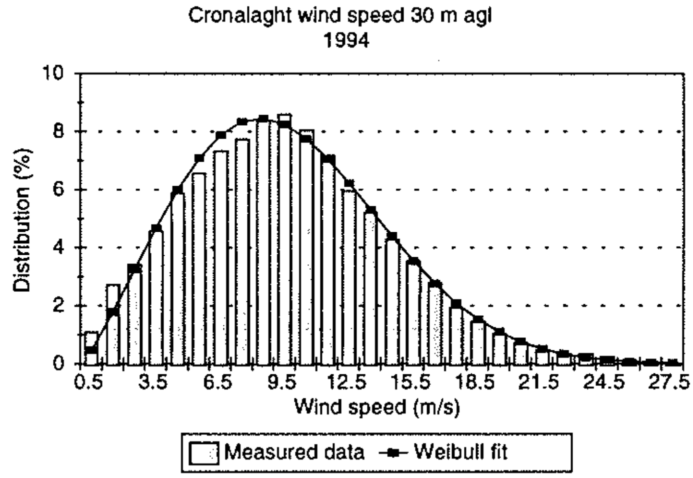

Figure 3 Wind speed distribution and Weibull fit for measured wind speeds at Cronalaght wind farm site in 30 m agl. Data from 1994.

Risø calculated the production of a Vestas V39 600kW machine as it would have been had the turbine been standing on the location of the measuring mast (co-ordinates (184200,423920), 115 m agl) for all of 1995:

Mean wind speed:	9.8m/s
Weibull *A*:	11-1m/s
Weibull *K*:	2.26 Energy density: 984. W/w^2
Production:	2.547 GWh/$_y$

9 Description of the Power System in County Donegal

The power system of County Donegal is interconnected with the national grid of Ireland. The power supply system of Ireland consists of 220 MW of hydro power plants, a pumped storage unit of 292 MW and 3540 MW of thermal power plants (status 1992). The power transmission take place at 400, 220, 110 and 38 kV. County Donegal is connected to the national grid via a 110/38 kV sub-station at Letterkenny and a 110/38 kV sub-station at Binbane. The County Donegal grid consists of three 38 kV circuits:

1. Coastal circuit between Letterkenny and Binbane.
2. Inland circuit between Letterkenny and Binbane via Stranorlar.
3. Inishowen circuit from Letterkenny to Buncrana, Cardonagh and Moville.

The 38 and 110 kV distribution and transmission system in County Donegal is shown in Figure 4 and Figure 5.

The power is distributed to the consumers in the area via 10 kV feeders and 10/0.4 kV transformers. New power generation units like wind turbines are required by the utility to be connected to the 38 kV line with a separate transformer.

Considering the favourable wind resources in County Donegal with sites with annual average wind speeds above 8 m/s in 10 m height, and that the potential for expanding the power supply capacity with hydro power is limited, future increase in the wind power capacity in County Donegal is an obvious method for meeting the future energy demand. Certainly, a number of wind farm projects are already initiated, see above sections.

In the current project focus has been on the first 38kV circuit (Coastal circuit).

The voltage limits for the 38kV network are 38Kv±8%.

Figure 4 ESB 38 kV distribution system in County Donegal, Ireland.

Figure 5 ESB 110 kV transmission system in County Donegal, Ireland.

The Letterkenny - Derrybeg - Binbane 38 kV circuit information enclosed as Appendix 1 has been provided by Andy Hanson from ESB from ref. 2. The circuit is open at Derrybeg, so Letterkenny 110/38 kV station feeds power to loads between Letterkenny and Derrybeg, and Binbane 110/38 kV station feeds power to loads between Binbane and Derrybeg (both included). The pumped storage & wind farm sites identified are all close to the Letterkenny - Derrybeg part of the circuit, and hence the load flow analysis is limited to this part of the circuit.

The specification of the Letterkenny - Derrybeg 38 kV feeder and loads is given in Figure 6. For the load flow analysis the loads are assumed to have a power factor of 0.8, except for the wind farm at Cronalaght which is assumed to be operated at a fixed power factor of 0.95 (consuming reactive power while producing active power).

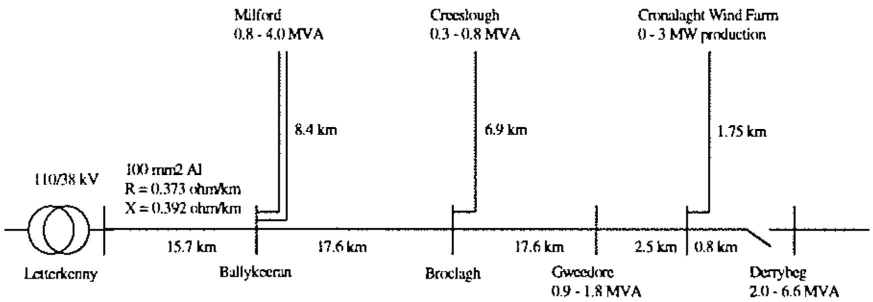

Figure 6 Data for Letterkenny - Derrybeg 38 kV feeder with indication of minimum and maximum loads.

10 Pumped Storage Potential

Five potential sites for pumped storage and wind farms have been identified. These sites are all relatively close to the coastal circuit between Letterkenny and Binbane. The case study will select the best of the five potential sites as a case study. The study assumes 1998 to be the year of installation.

Table 2 gives approximate design and cost data for some potential pump-storage hydroelectric schemes in Co. Donegal. The sites were chosen to a great extent because of their proximity to the existing 38 kV transmission grid in the north west of the county. Similar criteria were applied to all sites, such as the assumption of one metre increase in elevation level of all lakes to provide storage, and an approximate water velocity of two metres per second in all Pent-stocks for design purposes.

There is therefore significant scope for optimisation and reduction of per unit costs.

Please note that engineering, supervision and financing costs could add 10 % to the totals given.

Also, other factors could have a large economic effect, such as the net hydropower contribution of each site. It should be noted that L. Salt is in use as a public water supply reservoir. Any proposals for its use would have to be assessed very carefully in order to ensure that they would result in a net benefit to the water supply system. All the sites listed are two-lake systems, with the name of the upper lake given.

Table 2 Specification of technical data for pumped storage hydro power plants potentially to be installed at the given locations.

	L. Adinn	**L. Glentornan**	**L. Atirrive**	**L. Altan**	**L. Salt**
Map reference	189/422	188/417	190/416	194/423	212/426
Power Output (kW)	650	11,000	7,500	8,000	6,000
Pump Capacity (kW)	900	16,000	10,000	11,000	8,000
Energy Storage (kWh)	5,200	88,000	60,000	64,000	48,000
Head Height (m)	62	210	310	280	80
Penstock Section (m. sq.)	0.656	3.47	1.519	1.822	4.77
Penstock Length (m)	1,500	2,600	3,000	1,380	405
Water Storage (m^3)	37,800	200,000	87,500	105,000	275,000
Length to 10/38 kV (km)	1.2	2.35	1.75	6.5	7.9
Penstock (ECU)	500,000	4,300,000	1,980,000	990,000	680,000
Civil Works (ECU)	186,000	1,240,000	620,000	620,000	990,000
Turbine/Pump (ECU)	420,000	3,720,000	2,600,000	2,725,000	3,100,000
Grid Connection (ECU)	80,500	105,000	93,000	192,000	223,000
Total Investment (ECU)	1,186,500	9,365,000	5,293,000	4,527,000	4,993.000
Total Investment (ECU/kW_{out})	1825	851	706	566	832

At all sites reasonable locations for wind farms or wind turbines with capacity around the pumped storage capacity can be found. Map copies are enclosed as Appendix 3.

During week 29 in 1997 representatives from Risoe, ESBI and Scan Services went to Donegal to investigate a number of potential upper and lower lake systems. These had been previously identified by the ESBI as warranting some further on-site investigation. Below is a description of each of the sites visited. ScanEES Ltd. brief included, to check the current planning and environmental designation of the potential site in the Donegal Development Plan.

Lough Adinn
Grid Reference: 189 422

> Lough Adinn is located in the Carntreena Mountains near Cronalaght Mountain. It is approximately 60 metres above and 1.5 km away from the lower laker, Lough Nacung. The on site estimated energy output from this system was approximately 500-750 kW.
>
> The slopes of Cronalaght and the Carntreena Mountains are designated areas of high amenity value. This is according to the County Donegal Development Plan of 1988. An updated development plan is currently being compiled. The bottom lake, Lough Nacung is designated an area of scientific interest.

Lough Glentornan
Grid Reference: 188 417

Lough Glentoran, the top lake is located on Crocknafarrach Mountain and it lies approximately 200 metres above and over 2 km away from the lower lake, lough Nacung. The estimated, on-site, power output from this system was in excess of 10 MW.

Most of Crocknafarrach is undesignated, however, as mentioned above Lough Nacung is an area of scientific interest.

Lough Atirrive
Grid Reference: 190 416

Lough Atirrive is located on the north eastem slope of Addernymore mountain, west of the Derryveagh Mountians. It lies approximately 310 metres above Lough and in excess of 2.5 km away. The estimated output from this system is approximately 7.5 MW.

The lough itself is not designated, however the area to the north is an area of especially high amenity. The area to the west and south is free from designation.

Lough Altan
Grid Reference: 194 423

Lough Feeane is located in the Valey between Aghla More and Aghla Beg Mountians, north east of Errigal Mountain. It lies approximately 275 metres above and in excess of 1250 metres away from Lough Altan, the lower lake. The estimated power output from this system is approximately 5-10 MW.

Lough Altan, Lough Feeane and the Aghla More Mountain are designated areas of high amenity.

Lough Salt:
Grid Reference: 212 426

Lough Salt is located on Lough Salt Mountain. It lies approximately 80 metres above and 400 metres away from Lough Greenan, the lower lake. The estimated output from this system is 5-8 MW.

The area between Lough Salt and Lough Greenan is an area of high and especially high amenity. The top of Lough Salt Mountain and Crockalaght Mountain appear to have no designation. The south-south-western slopes of Lough Salt Mountain are also undesignated.

Lough Salt is used as a public water supply lake. However, according to the Department of the Environment this lake could be used in a pumped storage system provided the water quality of the lake does not deteriorate too much.

The present Donegal Development Plan is from 1988. An updated development plan has been under preparation for a number of years, but it has not yet been either published or approved. Scan Services has been in contact with the planning authorities in County Donegal. It has not, however, been possible to get an indication of which sites may be the most suitable for a demonstration project from a planning point of view.

11 Definition of Scenarios

The following scenarios have been investigated, Table 3.

Table 3 Scenarios investigated.

	Wind Turbine Capacity	Pumped Storage	Grid Reinforcement	Comments
Base Case	5*600kW	-	-	Current situation
Pumped storage	11*600kW	-	-	
@ Gweedore	11*600kW	5MW, 64 MWh	-	
(Lough Altan)	11*600kW	-	15.7+17.6km	
Pumped storage	8*600kW	-	-	
@ Ballykeeran	8*600kW	8MW, 48 MWh	-	
(Lough Salt)	8*600kW	-	15.7km	

The size of the wind farms have been chosen so that the energy consumption of the feeder could be supplied be wind energy. Based on this the necessary rating of the pump/generator has been determined in order to avoid steady state over-voltages in the worst case (low load, high wind). The system is then simulated using SimStore and the installed wind farm capacity is reduced in order to avoid dumping wind energy due to full storage in situations with high grid voltage.

The consumption of the feeder is based on assumption on the load pattern and is taken to be equal to the middle value between low and high load. This equals approx. 12*600 kW installed wind farm capacity.

The wind turbines are assumed to be installed at Cronalaght. The installed capacity is the total capacity at Cronalaght including the existing 5*600kW.

12 Steady State Voltage Analysis

The feeder from Letterkenny to Derrybeg can only absorb a limited amount of wind power if over-voltage situations are to be avoided due to the impedance of the feeder. The feeder is operated so that the voltage at the outgoing feeder at Letterkenny is at the maximum allowed value (38kV+8%) in order to maximise the allowable load of the feeder.

In Figure 7 is shown the amount of wind power that can be absorbed at Cronalaght in the case of minimum consumer load. In the left hand side of the figure is the steady state voltage of the Cronalaght bus bar shown as a function of the amount of wind energy fed into the grid at the same point. It can be seen that the voltage limit is violated when the amount of wind power exceeds approx. 2.8MW. Currently is 3MW installed in a wind farm there. The voltage profile of the feeder is shown in the right hand side of the figure. The voltage profile is shown for cases with minimum and maximum load and minimum and maximum wind power. As expected is the voltage limit violated in the case of minimum load and maximum wind power even if it is only with a small amount. In order to avoid this situation is the wind farm equipped with a so-called Voltage Control Unit (VCU). This device limits the output power of the wind farm in situations where over-voltage can occur.

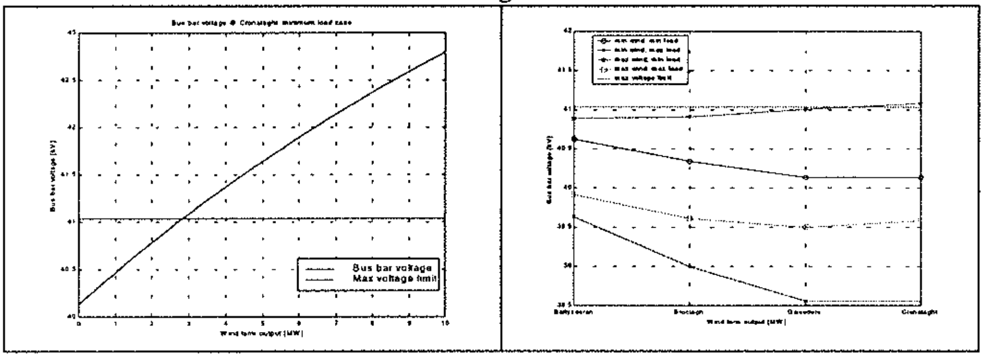

Figure 7 Steady state voltage @ Cronalaght vs. amount of wind power in the minimum load case (left side). Voltage profile for feeder in different load cases (Right side)

The results in Figure 7 show that there is no room for installation of additional wind turbine capacity without inclusion of some sort of control.

12.1 Input to SimStore

In order to assess the technical performance of the different options that include pumped storage StorSim has been used. The input sequence of wind and load as well as the resulting wind turbine output are shown in Figure 8. The time series duration is 4 weeks. The time step of the simulation is 10min. It is noticed that the load has a pronounced diurnal pattern and that the wind covers a large range.

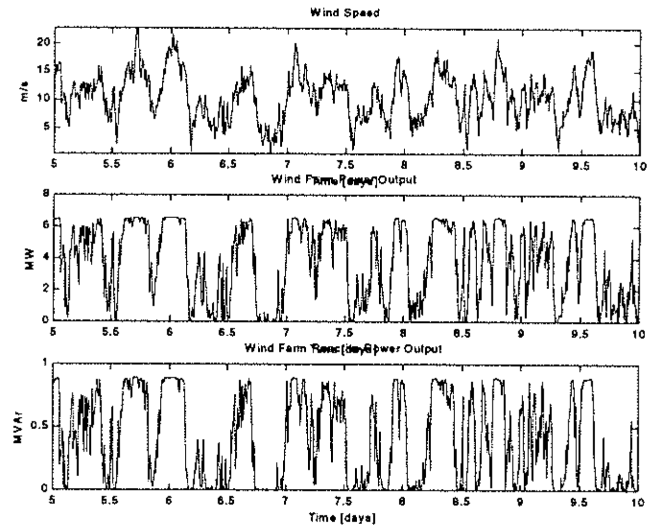

Figure 8 Wind speed and wind farm output.

The load input, Figure 9, consists of three time series one for each of the load centres: Milford (connected at Ballykeeran), Creslough (connected at Broclagh) and Gweedore. The output from the wind farm and the load from the load centres are the input to the simulation.

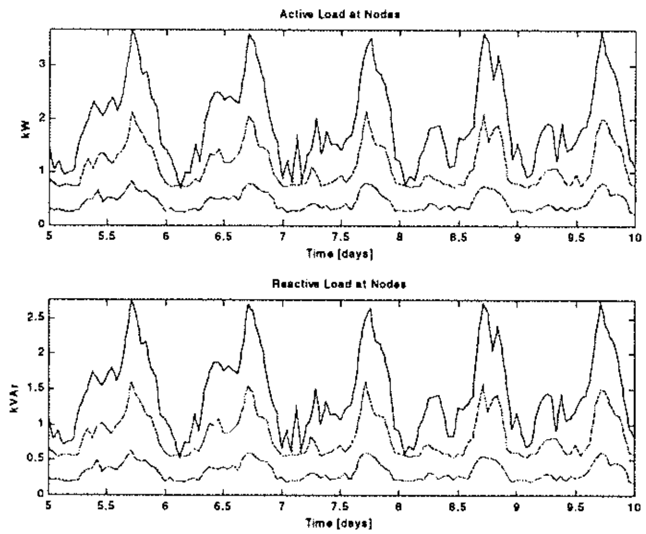

Figure 9 Load time series for SimStore simulations.The load consists of three load centres Milford (connected at Ballykeeran, top), Creslough (connected at Broclagh, middle) and Gweedore (bottom).

12.2 Current situation

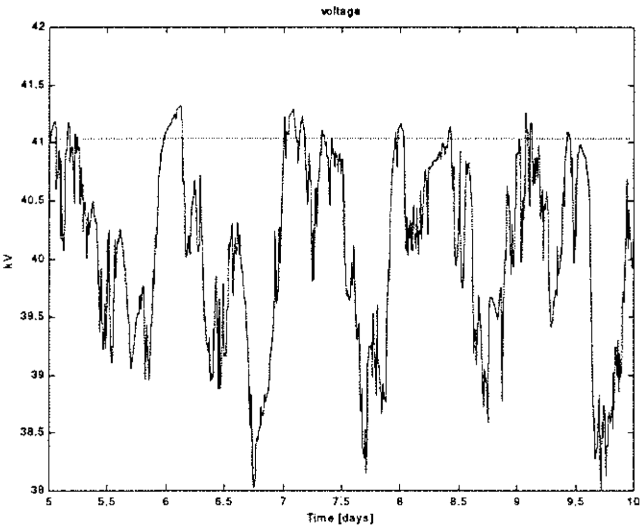

*Figure 10 Grid voltage for the current situation (5*600kW) but without VCU operation.*

The results of a simulation of the current situation with 5*600kW wind turbines installed at Cronalaght are shown in Figure 10. In this figure the VCU is not operated and it can be seen, as expected, that over-voltage situations occur. When the VCU is operated the over-voltage situations will be eliminated but some of the wind energy has to be dumped. The amount of energy that has to be dumped is estimated to be 256MWh/y or less than 2% of the total wind farm production.

12.3 11*600kW wind turbines at Cronalaght and pumped storage at Gweedore

In this scenario additional 6*600kW wind turbines are installed at the Cronalaght wind farm so that the total installed capacity is 11*600kW. Because the output from the wind farm will be above the limit that can be absorbed by the grid without violating the voltage limit the extended wind farm is combined with a pumped storage plant connected to the grid at Gweedore. The rating of the pumped storage plant is 5MW and 64MWh.

The resulting steady state voltage profiles for the feeder are shown in Figure 11. The figure shows how the addition of the pumped storage can lower the grid voltage by adding load in the low load situations. The extra load absorbs the excess wind power. The voltage in the worst case situation is now well below the upper voltage limit.

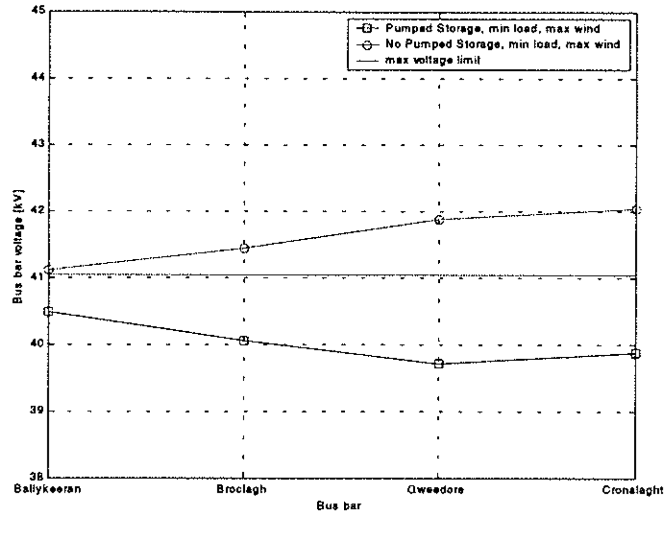

*Figure 11 Steady state voltages in the 11*600kW wind farm case with pumped storage at Cronalaght.*

The simulated time series of the voltages at the Cronalaght bus bar are shown in Figure 12, both with and without the pumped storage plant. The left part of the figure shown the total simulated time series and the right part shows the time interval from day 5 to day 10. From the figure it is clearly seen how the over-voltage occurrences are eliminated. The voltage will at large part of the time be in an interval close to the voltage limit but it will not exceed since both the power rating and the storage size are large enough to accommodate for the wind power that needs to be buffered.

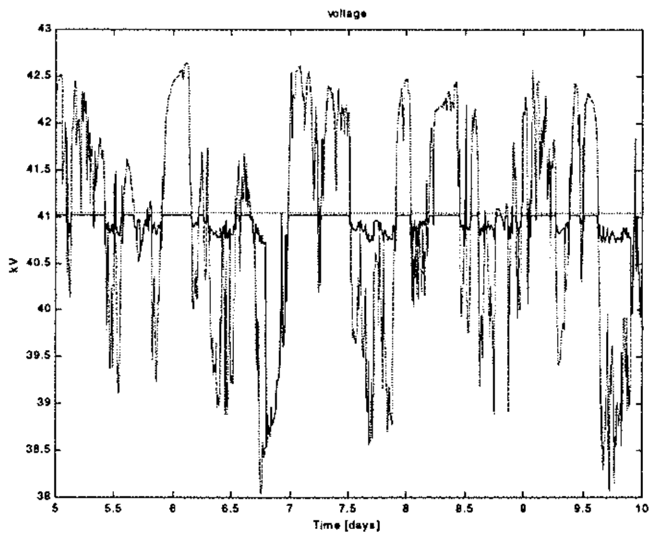

*Figure 12 Steady state voltage at Cronalaght with 11*600kW with and without storage.*

The next figure, Figure 13, shows that the storage is capable of buffering the energy needed. It is very close to being full at approx. 21 day. The minimum storage level is 40% SOC, which is a quite high value. This value is the same as for battery storage. If the value was lowered the amount of wind energy that can be buffered would of course be increased. The figure also shows that for large amount of the time there is an wind energy surplus that has to be buffered. This is due to the large installed capacity compared to the maximum that can be installed without any power control options. If the amount of installed capacity is too high it will be impossible to feed the energy back to the grid.

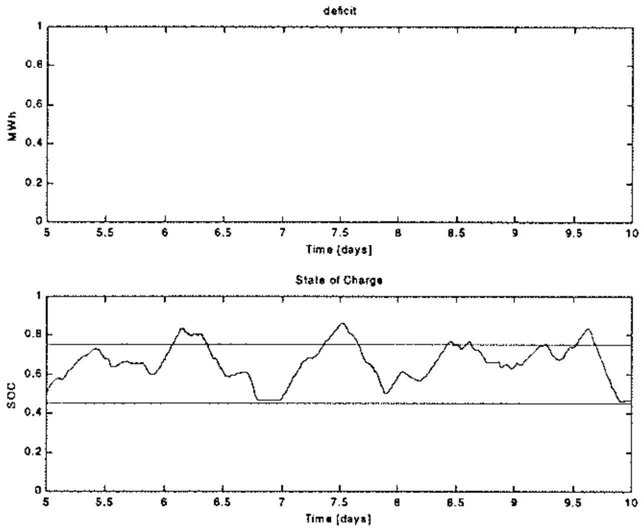

*Figure 13 Storage energy deficit and state of charge for 11*600kW case*

The calculations show that a wind farm of a total capacity of 11*600kW combined with a pumped storage plant of 5MW and 64MWh will result in a combined system that can deliver most of the required energy to the feeder without over-voltage occurrences. The amount of installed wind power might be increased if the operating conditions of the storage are changed.

12.4 8*600kW wind turbines at Cronalaght and pumped storage at Ballykeeran

In this case an additional amount of 3*600kW of wind power is installed at Cronalaght and it is combined with a pumped storage plant that is connected to the grid at Ballykeeran. Ballykeeran is the first bus bar on the feeder after Letterkenny. Cronalaght is at the far end of the feeder. In order to be able to ensure that the voltage can be lowered below the voltage limit when the load is low and the wind farm output is high the rating of the pumped storage system has to be higher than in the case where the wind farm and the pumped storage plant are connected to the grid in the same point.

The steady state voltages for the feeder with and without pumped storage are shown in Figure 14. It is noticed that the voltage profile is very different from the voltage profile in the previous case. In the current case is the voltage increasing all the way to the wind farm whereas in the previous case the voltage was decreasing from the Letterkenny bus bar until Gweedore with the pumped storage plant and only increasing in the last section between Gweedore and Cronalaght. It is also noticed that the voltage level at Cronalaght is higher in the current case even though the installed capacity is decreased and the rating of the pumped storage plant is increased.

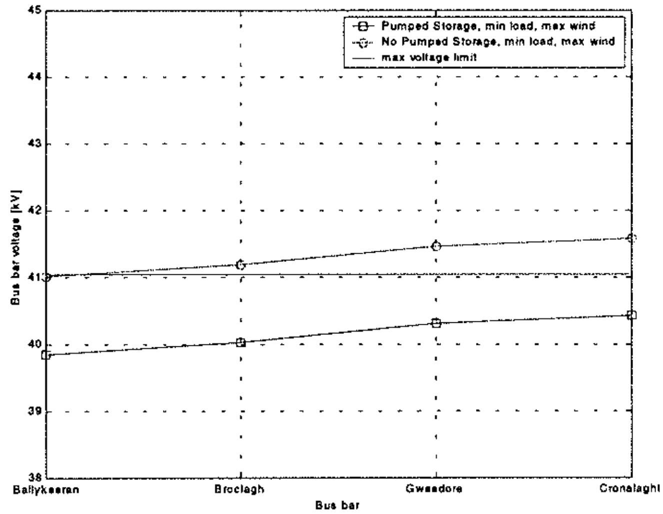

*Figure 14 Steady state voltages at the Cronalaght bus bar in the 8*600kW case with and without pumped storage at Ballykeeran*

The steady state voltage time series simulated for the case with 8*600kW with and without are shown in Figure 15. As in the previous case the inclusion of the pumped storage plant eliminates the over-voltage situations. The rating of the pump is adequate as shown on Figure 14 but the size of the reservoir can only almost absorb the amount of energy needed in order to avoid over-voltage situations in the given scenario. It can be seen that two situations with over-voltage occur. The first one is also shown in the detailed figure on the right hand side of the figures. It occurs at 7.5 days. The limiting factor is the size of the reservoir as can be seen on the figure with the state of charge, Figure 16. The second and larger one occurs at ca. 21 days. In both cases is the reservoir full. If the operating limitations of the storage are changed in order to allow a lower minimum SOC these situations can be avoided.

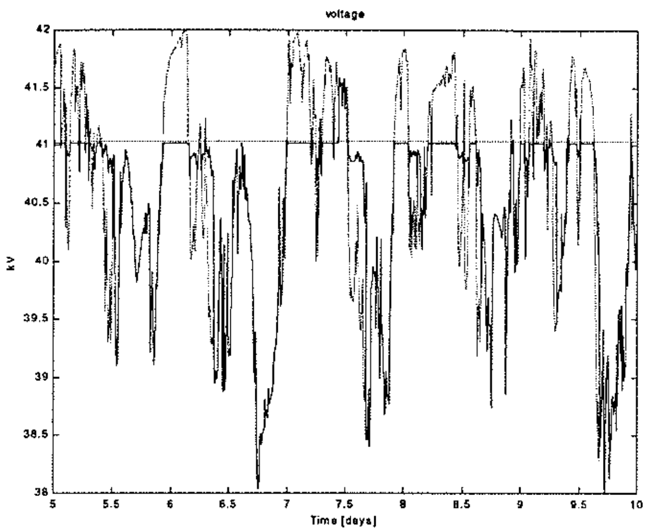

*Figure 15 Steady state voltage time series for the 8*600kW case with and without storage.*

In Figure 16 is the corresponding energy deficit and SOC time series shown. It can be seen on the figures that the above mentioned full storage situations occur. The result of that is that some of the wind energy has to be dumped (storage energy capacity deficit). It is worth noticing that the pattern for charging and discharging the storage is a bit different from the case above. For a significant amount of the time the storage is at minimum charge and it then has to absorb a large part of the wind farm output in a short time and it then released shortly after as the voltage decreases.

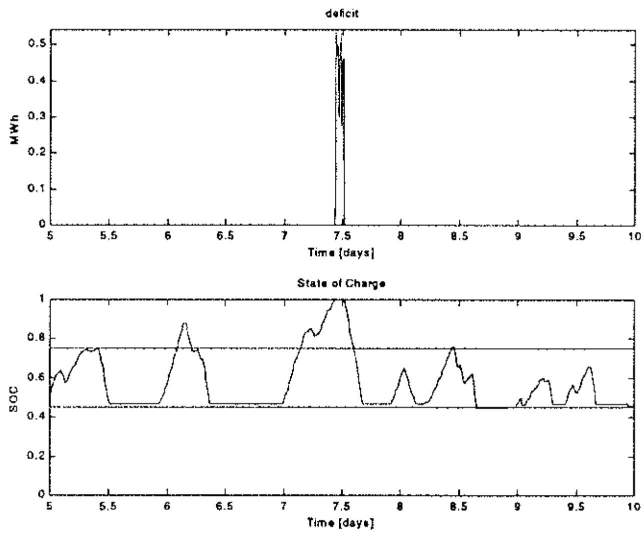

*Figure 16 Storage energy deficit and state of charge for 8*600kW case*

The two major findings in this scenario are that the amount of wind energy that can be absorbed by the grid is reduced even if the rating of the pump is increased. The increase in pump rating is a result of the connection of the storage plant at a point on the feeder closer to the substation. The decrease in wind farm installed capacity is a result of the smaller storage capacity compared with the previous scenario. The incentive for including the scenario is that some of the cost might be shared with the water utilities since the upper lake is used as a drinking water resource.

12.5 Grid reinforcement

The alternative to installing a pumped storage plant or dumping excess wind energy is to reinforce the grid. The assumption is that the grid is reinforced in sections between the bus bars.

In order to determine how the grid is to be reinforced in order to avoid over-voltage situations the following procedure has been executed. The voltage at Cronalaght has been determined in the case of no wind and maximum load for the current grid situation with the bus bar voltage at Letterkenny at the maximum voltage limit. The bus bar voltage at Cronalaght in this situation is then used to determine the Letterkenny bus bar voltage in the same load situation but with the grid reinforced. This voltage is then used in order to determine the amount of wind power that can be absorbed without over-voltage situations occurring and without any power control schemes.

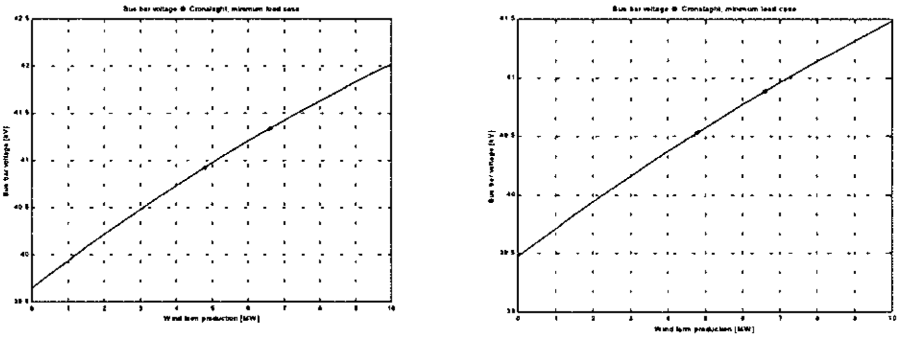

Figure 17 Grid reinforcement. On the left hand side is shown the steady state voltage as a function of the output from the wind farm when the grid is reinforced between Letterkenny and Ballykeeran. On the right hand side is the grid reinforced from Lettekenny to Broclagh.

Using this procedure the voltage of the Cronalaght bus bar has been calculated as a function of the wind farm output for two different grid reinforcement situations, Figure 17. In the left hand side of the figure is the grid reinforced between Letterkenny and Ballykeeran (15.7km). It can be seen that this is adequate in order to install 8*600kW at Cronalaght whereas it is necessary to reinforce the next section (total: 15.7km + 17.6km) if 11*600kW is to be installed and over-voltage problems are to be avoided

13 Economic Comparison of alternatives

The total costs of the different alternatives are calculated and compared. The basic assumption is that the costs the wind turbines and the installation of them are outside the costs included. The only costs included are the investment in additional equipment or grid reinforcement and the value of the energy lost. The lost energy is either dumped or it is lost in the pumped storage plant.

The investment in the pumped storage plant at Gweedore is assumed to be between ½ and 2/3 the specific cost of the plant at Lough Altan in Table 2. The cost of the system at Ballykeeran is taken as the cost of Lough Salt in the same table. The pumped storage plants are given a capacity credit of 2/3 of the rating and the cost is equivalent to the cost of installation of a gas turbine, 670 ECU/kW.

The cost of the grid reinforcement is assumed to belong to the interval from 30kECU/km to 40kECU/km since the figure given by ESB is 35kECU/km.

The value of the energy is assumed to be 0.04ECU/kWh. The losses in the grid are neglected. This includes the reduced losses due to grid reinforcement.

The project life time is 20 years and the interest rate is 5% p.a.

Table 4 Total investment of the different alternatives.

		Imin	Imax	Capacity Credit	Itot,min	Itot,max
		kECU	kECU	kECU	kECU	kECU
5*600kW	Base Case	0	0	0	0	0
11*600kW	No storage, No grid reinforcement	0	0	0	0	0
11*600kW	Pumped storage @ Gweedore	2264	3018	2233	30	785
11*600kW	Grid reinforcement (15.7+17.6km)	999	1332	0	999	1332
8*600kW	No storage, No grid reinforcement	0	0	0	0	0
8*600kW	Pumped storage @ Ballykeeran	4993	4993	3573	1420	1420
8*600kW	Grid reinforcement (15.7km)	471	628	0	471	628

The investment in pumped storage plants is heavily reduced by the value of the capacity credit. The result is that in the 11*600kW case the pumped storage alternative has the lowest investment. In the 8*600kW case the grid reinforcement has the lowest investment.

Table 5 Energy losses and value of energy losses for the different alternatives.

		Es-tor,loss	Edump	Value of loss
		MWh	MWh	kECU
5*600kW	Base Case	0	256	127
11*600kW	No storage, No grid reinforcement	0	7104	3541
11*600kW	Pumped storage @ Gweedore	1685	77	883
11*600kW	Grid reinforcement (15.7+17.6km)	0	0	0
8*600kW	No storage, No grid reinforcement	0	7313	3645
8*600kW	Pumped storage @ Ballykeeran	1682	352	1014
8*600kW	Grid reinforcement (15.7km)	0	0	0

The grid reinforcement is designed so that it is not necessary to dump any wind energy. The losses are therefore zero in the grid reinforcement cases. The losses in the two other types of case, pumped storage and no storage, no reinforcement, are calculated on the basis of the SimStore simulations. It is noticed that the value of the losses is higher in the case of 8*600kW than in the case of 11*600kW due to the increased amount of dumped energy.

Table 6 Total cost of the different alternatives.

		Tc,min	Tc,max
		kECU	kECU
5*600kW	Base Case	127	127
11*600kW	No storage, No grid reinforcement	3541	3541
11*600kW	Pumped storage @ Gweedore	913	1668
11*600kW	Grid reinforcement (15.7+ 17.6 km)	999	1332
8*600kW	No storage, No grid reinforcement	3645	3645
8*600kW	Pumped storage @ Ballykeeran	2433	2433
8*600kW	Grid reinforcement (15.7km)	471	628

Comparing the total cost of the different alternatives indicates that for the case of 8*600kW that least cost option is grid reinforcement. Even if the investment in the pumped storage was halved because of cost sharing with water supply grid reinforcement would still be the least cost option.

In the case of 11*600kW the cost of grid reinforcement and pumped storage are in the same range. It is necessary to investigate further mainly the assumptions behind the cost estimate of the pumped storage plant in order to find out if this option can compete with grid reinforcement.

The options can also be compared with the installation of a gas turbine delivering the same amount of energy.

The fuel cost are taken as the current world market price (Jan 1999), 101USD/t or 87ECU/t. The efficiency of the gas turbine is assumed to be 35%. The energy content of the fuel is 11.86 kWh/kg.

The energy production is taken to be the same as the energy delivered to the grid by either the 6*600kW wind farm combined with the pumped storage plant or the 3*600kW in the case of grid reinforcement.

The investment in the wind farm is assumed to be 1.350kECU/kW including foundation and grid connection.

The fuel cost of energy from the gas turbine can be calculated as

$$\frac{1}{\eta}*\frac{1}{E_s}*C_f=\frac{1}{0.35}*\frac{1}{11.86}*87=0.021ECU/kWh$$

<u>11*600kW case</u>
The total energy delivered to the grid is (from the simulations) 14.995MWh.

An estimate of the levelised production cost (LPC) is in Table 7

*Table 7 Levelised production cost of energy in the 11*600kW case*

Wind Farm		Gas Turbine	
Wind turbine investment	4860 kECU	Investment (Capacity credit)	2233 kECU
Pumped storage investment	3018 kECU	Fuel cost	3918 kECU
Total	7878 kECU	Total	6151 kECU
LPC	0.042 ECU/kWh	LPC	0.033 ECU/kWh

The break even fuel cost can be calculated to be 125 ECU/t. This value is 50% higher than the current world market price but the current world market price is extremely low.

<u>8*600kW case</u>
The total energy delivered to the grid is (from the simulations) 7970MWh. This scenario is different from the previous one in that there is no storage involved. It is then taken here to mean that there will be no need to install new generation capacity. The singly cost in the gas turbine case is then the avoided fuel cost.

An estimate of the levelised production cost (LPC) is in Table 8.

*Table 8 Levelised production cost of energy in the 8*600kW case*

Wind Farm		Gas Turbine	
Wind turbine investment	2430 kECU	Investment (Capacity credit)	0 kECU
Grid reinforcement	628 kECU	Fuel cost	2085 kECU
Total	3058 kECU	Total	2085 kECU
LPC	0.031 ECU/kWh	LPC	0.021 ECU/kWh

The break even fuel cost can be calculated to 126 ECU/t. This value is, again, 50% higher than the current world market price but the current world market price is extremely low.

The estimates above are very rough, but they indicate the order of magnitude of the production costs involved. There are several aspects that have to be taken into account. These include:

- is it necessary to install dispatchable power plants in the region;
- will the investment in pumped storage plants be outdated by the building of a new 110kV line in the region;
- the calculation is very sensitive to the fuel cost. Will they stay low;
- to which degree is the industrial development limited by the capacity of the grid.

Only detailed considerations by the planning people involved can answer these question. It is outside the scope of this project.

14 Social and Economic Impact

The lack of a sufficient electricity infrastructure in Co. Donegal is presently hampering the economic development in the Country. As a conference held on the 28th March 1998:

"Strengthening the Economy of Peripheral Regions"

in Letterkenny, Co. Donegal it was acknowledged by the Industrial Development Agency (IDA) that the lack of a sufficient electricity infrastructure in the North West of Donegal was hampering investment. To expect industry to arrive first and then plan for electricity requirements would not work because of the long time lag in getting the electricity infrastructure in place.

The conference, which was hosted by Donegal County Council, The Border Regional Authority, Letterkenny Institute of Technology and Letterkenny Chamber of Commerce and Industry, focused very strongly on the vital role electricity infrastructure played in the economic development of the region. From the ESB it was acknowledged that the demand for electricity in Donegal is increasing at far higher levels than the national average.

At present the NorthWest region of county Donegal is only served by a 38kV loop from Letterkenny to Binbane (see Alterner project for details). In the industrial estate in Bunbeg area alone there are 1000 people employed in industrial jobs. It is generally accepted that the area can hardly accept any new industry with even a moderate electricity load.

ESB has acknowledged the problem and has recently announced plans to erect a 105 kilometres of a 110kV line from Letterkenny to Binbane in Frosses, which will incorporate the building of an ESB substation in Gweedore near the 3MW Cronalaght windfarm and the now disused 5MW ESB turf fired power station. The estimated cost of this development is £13 mill and the ESB has recently indicated that it hopes to be in a position to apply for planning permission for the 110kV line in July 1998. Agreement has been made with Donegal County Council for the proposed route, discussions will now begin with landowners.

In the North East of Donegal the ESB is involved in the construction of a 34 kilometres of a 110kV line between Letterkenny and Buncrana. This involves the building of a distribution station in Buncrana; the overall cost is estimated at £3 mill.
The third element is the provision of a 38kV station at Killybegs to facilitate the industrial demands in Ireland's largest fishing port. In Letterkenny a Static Var Compensator will be installed to provide a steady voltage throughout North East Donegal to alleviate interruption in voltage. This is funded under the EU Interreg Programme.

The long term plans are to secure a long term supply into Donegal and one of the outcomes being considered if the peace process continues is an inter-connector from Donegal into Northern Ireland.

The two main factors identified as being most important for the industrial development and job creation of County Donegal is:

- continuation of the peace process
- the quality of the infrastructure incl. the electricity supply

References

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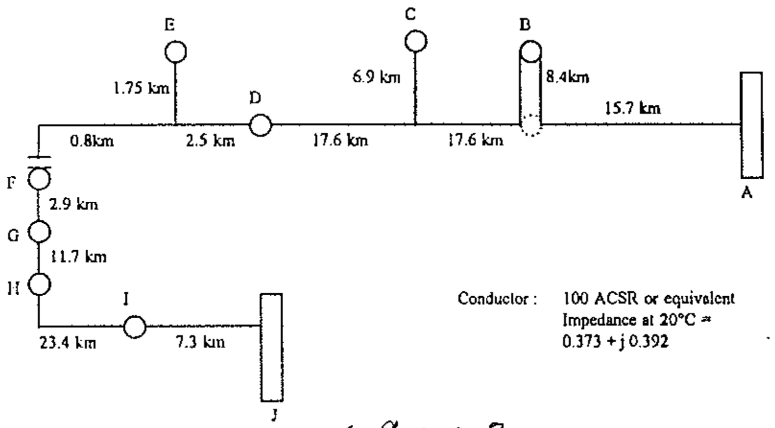
[2] O'Donnel, F., C. McMahon, Prefeasibility Study Guidelines on Optimum Locations for Connection to National Electricity Grid of Additional Capacity Derived from Renewable Energy Sources. ESB, August 1996.

[3] H. Bindner. Power Control for Wind Turbines in Weak Grids: Concepts Development. Risø-R-1118(EN), Roskilde, March 1999

Appendix 1 Letterkenny - Binbane 38 kV circuit information



$\cos\varphi = 0.8$

Code	Station	Peak Load (MVA)	Altener Min. Load (MVA)	Impedance to Source (r + jx referred to 41kV)
A	Letterkenny 110kV	49.3	-	1.07 + j 5.19
B	Milford	4.0	0.8	
C	Creeslough	0.8	0.3	
D	Gweedore	1.8	0.9	
E	Windfarm	-	-	
F	Derrybeg	6.6	2.0	
G	Clady Generating Stn.	-	-	
H	Dungloe	2.7	0.8	
I	Glenties	1.9	0.4	
J	Binbane 110kV	14.2	-	1.15 + j 7.45

Appendix 2 Wind climatological fingerprint

The purpose of the graphical presentations of wind data is to give a compact and informative overview of the measured wind data. The following text is from the European Wind Atlas (Risø 1989) and explains the enclosed climatological fingerprint.

The first line states the name of the meteorological station and the period over which the data were collected. This is followed by the height above ground level where measurements were taken, the mean value, the standard deviation and the mean value of the cube of the measured wind speeds. The graphical presentation consists of five graphs:

The mean year

The average seasonal variation of the measured wind speed (full line) and cube of wind speed (dashed line) is shown in the top left graph. All data associated with the same calendar month are averaged and the results plotted at the mid-point in each of the indicated monthly intervals. The unit on the ordinate is m/s for mean speeds and m^3s^{-3} for the mean of the cube of the wind speed. Values read from the graph must be multiplied by the scale factor given to the right. The continuous curves are obtained by interpolation using a periodic cubic spline. The speed data are also contained in the tables on the station description pages.

The mean days

The average daily variation of the measured wind speed for the months of January and July is shown in the top right graph. The average hourly variation of wind speed is shown in full lines for January and July and for the cube of wind speed dashed lines are used. Data from all months of January (July) associated with the same time of day are averaged. Results obtained for each of the indicated standard hours are plotted using an interpolating smooth curve (periodic cubic spline). The mean ordinate for each curve is identical to the ordinate on the corresponding mean year curve (top left graph) at the January (July) points. The unit on the ordinate is m/s for mean speeds and m^3s^{-3} for the mean of the cube of speed. Values read from the graph must be multiplied by the scale factor given to the left. Mean days for each calendar month are calculated and define - for each calendar month - a mean or reference day which is used as reference in calculating the spectrum below. The speed values are contained in the tables in the station descriptions.

The wind rose

The relative frequencies of winds coming from each of twelve sectors are shown in the middle left graph as the radial extent of the circle segments spanning the sectors (thick lines). The contribution from each sector to the total mean speed and to the total mean cube of speed are given as the narrower segments and the central segments respectively. For each quantity the normalisation is such that the largest segment extends to the outer dotted circle. The corresponding value for each of the three quantities is given in the small box in per cent (numbers given to the nearest integer). The inner dotted circle corresponds to half of this value.

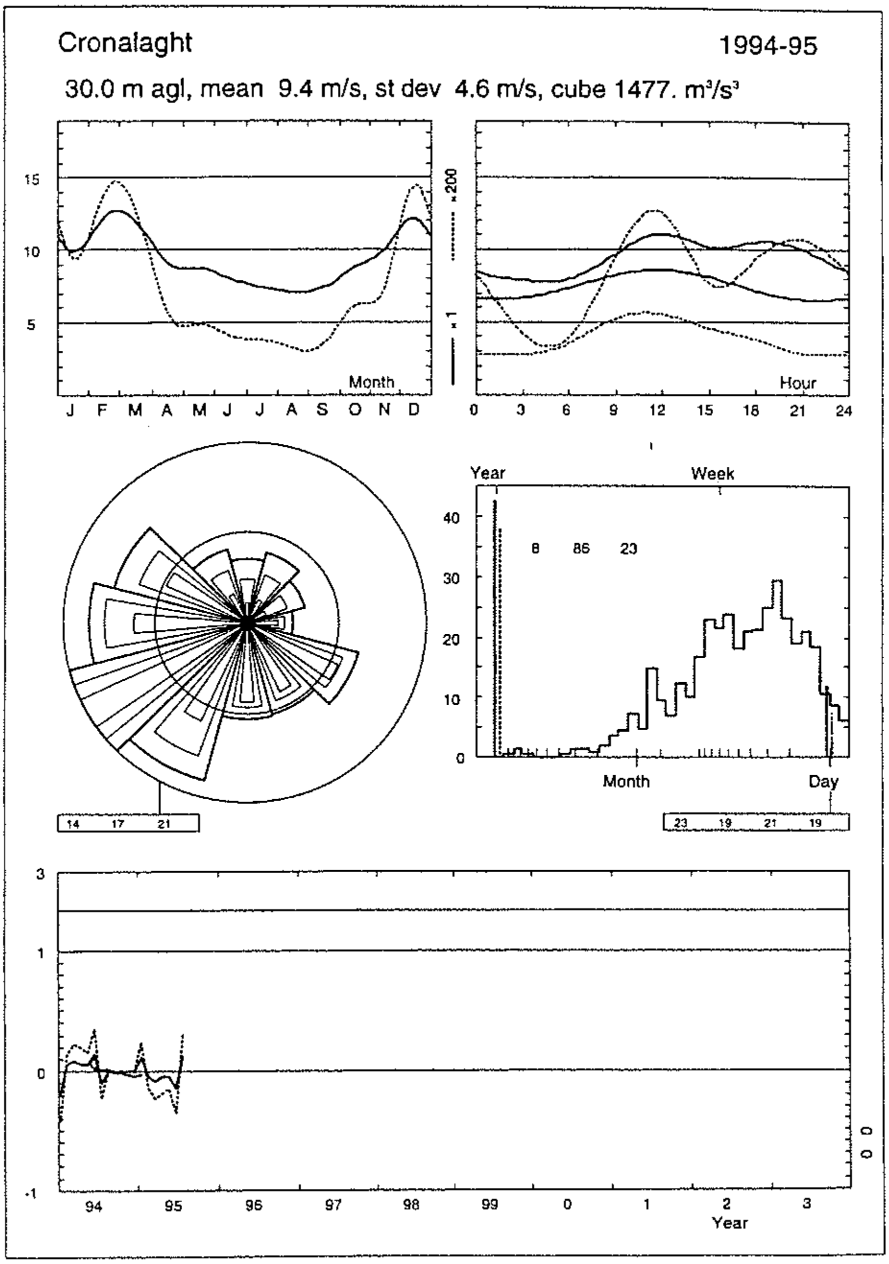
The spectrum

The contribution to the total variance of wind speed for a range of periods is shown by the full curve in the middle right graph. The vertical scale is arbitrarily adjusted to centre the curve. The abscissa gives the periods on a logarithmic scale. The curve is calculated from the total time series by first subtracting the monthly mean day values from each day data, hour by hour. The monthly mean days for all twelve months were calculated as described for January and July above. The mean days are in this context considered deterministic in contrast to the calculated time series of deviations which form the stochastic part. This is followed by a Fourier transform of the deviations and the spectral estimates are squared and block averaged over bands of equal relative bandwidth corresponding to the widths of the steps in the curve.

The full vertical bar on the left side gives the contribution to the standard deviation of wind speed in the whole set of data from periods which fit into one year. This is calculated as the standard deviation of the mean year (top left). The adjacent dashed bar gives similarly the mean year contribution to the standard deviation of the cube of wind speed. Units are per cent of the total standard deviation of the data. Similarly the bars on the right give the contributions to the standard deviations of speed and cube of speed by periods which fit into one day, i.e. 24, 12, 8 and 6 hours in the present case of basic 3-hourly data. The numbers listed at the top left inside the graph are the contribution to the total standard deviation in per cent by the random variations contained in the variance spectrum, divided into the part with periods longer than one year, periods between one year and one day, and periods smaller than one day (the sum of squares of the contributions of the three random parts together with the contributions from the deterministic mean year and mean day adds to unity). The numbers in the small box below the graph give the relative standard deviation for speed and cube of speed for the mean January day (first two numbers) and the mean July day (last two numbers).

The time print

The month-by-month relative deviation from the mean months is shown in the bottom graph. For each month the average speed and cube of speed is calculated and the expected value from the corresponding calendar month in the mean year (top left) is subtracted. The relative deviation is shown by the jagged lines -- full line corresponding to speed and dashed line corresponding to cube of speed. The smoother full line shows the year-by-year relative deviation of mean speed from the total average. Each point on this curve gives the relative deviation in the period extending backwards and forwards one half year (centred block averages). The centre value for each calendar year thus gives the deviation for that particular year. The open circles show similarly the relative deviation of the mean cube of speed for each calendar year. The numbers to the right give the root mean square of the calendar year deviations in per cent for speed (lower number) and cube of speed (upper number). The vertical scale is linear from -1 to +1, and shifts at +1 to a coarser linear scale which is adjusted to accommodate the largest deviations.


Cronalaght
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8 86 23
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23 19 21 19
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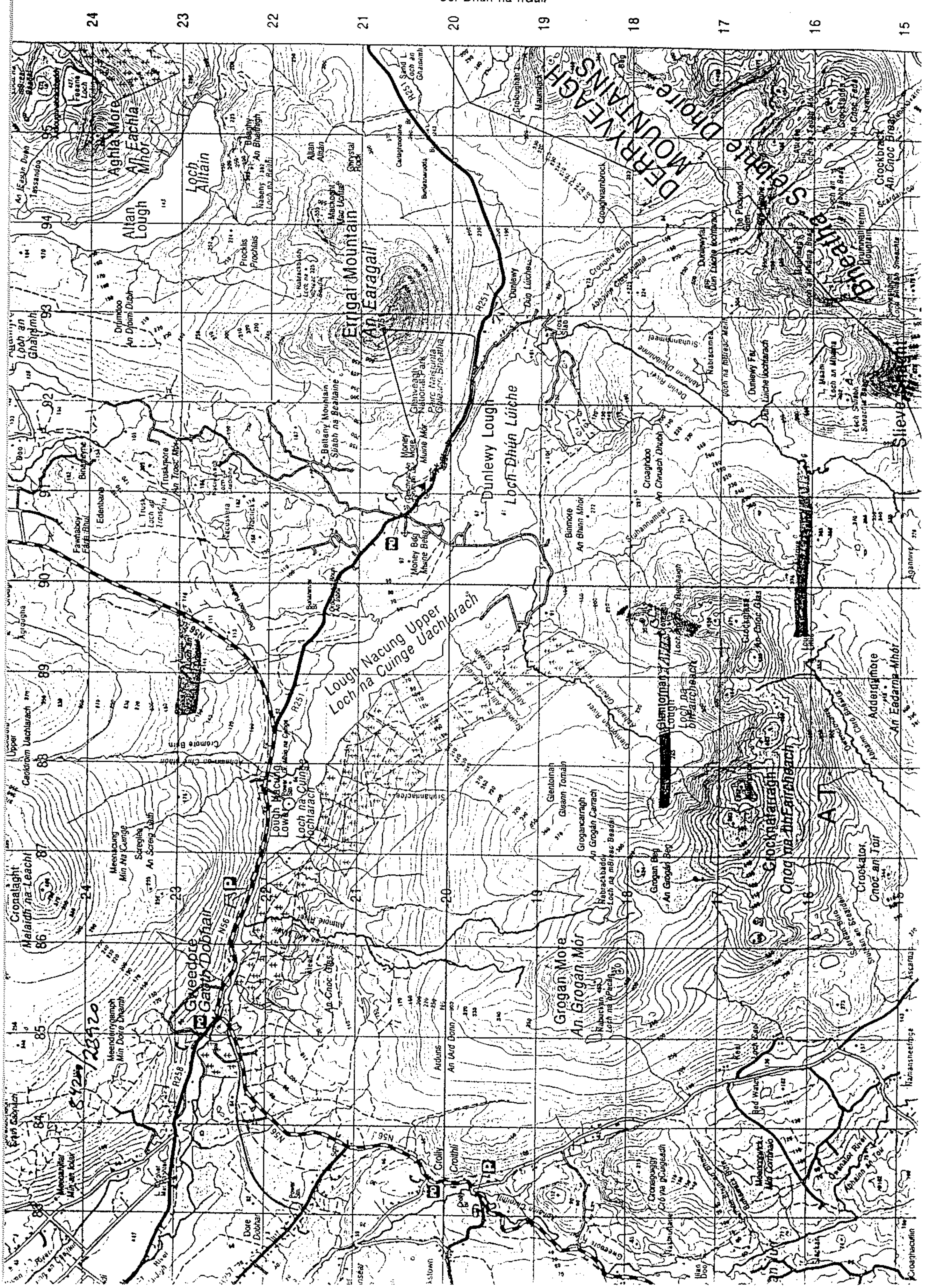
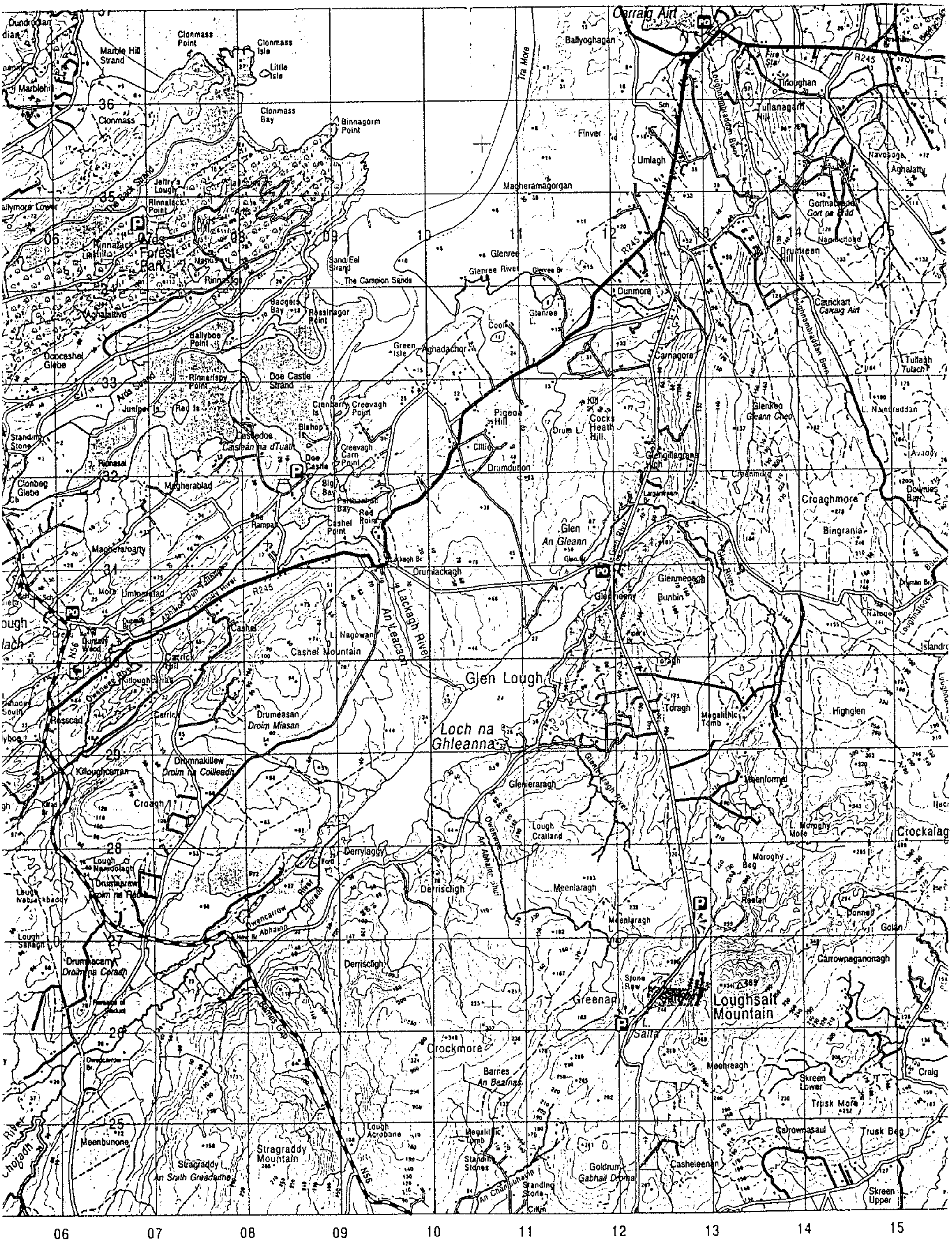
Year

Appendix 3 Site maps

The enclosed sites maps are copied from Discovery Series (Ordnance Survey 1995) 1 and 2 in 1:50000 scale and with 10 m contour interval.

Co. D O N E G A L
Co. Dhún na nGall





Co. DONEGAL

Co. Dhún na nGall

Bibliographic Data Sheet **Risø-I-1397(EN)**

Title and authors

Power Control for Wind Turbines in Weak Grids:
Donegal Case Study

Henrik Bindner, Inge Buckley, Patrick Murphy

Department or group	Date
Wind Energy and Atmospheric Physics Department	March 1999

Groups own reg. number(s)	Project/contract No(s)
	JOR3-CT95-0067

Pages	Tables	Illustrations	References
38	8	17	3

Abstract (max. 2000 characters)

The current report is a summary of the results of the case study done at Donegal in the context of the EU supported project 'Power Control for Wind Turbines in Weak Grids', contract no JOR3-CT95-0067. In this project various combinations of wind power, storage and control are studied in order to increase the amount of wind energy that can be absorbed economically at a given point in a weak grid.

The project consists of four main parts. The first part is concerned with the development of such systems. Mainly battery and pumped storage are considered as storage and different control strategies are studied. The second part is the development and test of a power control system using batteries. The third and fourth parts are two case studies in Madeira, Portugal and County Donegal, Ireland.

The scope of the analysis is to investigate if the amount of wind energy that can be utilised in Donegal can be economically increased especially seen from a power control point of view. The power system of Donegal is weak. This limits the both the amount of wind energy that can be installed and the consumer load, which limits the development of the region.

The main result is that with the current fuel prices the generation cost of energy using gas turbines is the least cost option. However, it is very important that future development in the fuel cost is taken into consideration before decisions on which option to chose.

An optimised design for a pumped storage plant could reduce the investment cost considerably and increases in the fuel cost is also likely to happen. The generation cost from wind energy in County Donegal is quite low due to the very good wind resource in the region. This combined with the increased certainty of the production cost during the life time of the installation make it worth while to consider installation of additional wind power in combination with a pumped storage plant.

One additional factor that has to be taken into consideration is the general development of the region. In this development an improved power supply can play a crucial role.

It is recommended that further investigations especially including local and utility planners in order to have a more complete picture of the development of the region and the possibilities and requirements for that development.

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